Experimental Validation of ASM-HEMT Nonlinear Embedding Modeling of GaN HEMTs at X-band

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Abstract—This paper presents the experimental results from a validation of a newly-developed nonlinear embedding model for the GaN ASM-HEMT model. An extracted ASM-HEMT model was used together with the nonlinear embedding model to synthesize on-wafer Class F operation at 10 GHz for a 150 nm 1W GaN HEMT. The embedding model provided a set of multi-harmonic terminations at the transistor’s source and load, which were then applied to the physical transistor in an experimental setup. The transistor’s performance with only the predicted load termination at the fundamental is compared with its Class F performance when terminated at the predicted fundamental, second, and third harmonic load terminations, as well as second harmonic source termination. Phase sweep of each harmonic termination is further used to verify that the terminations predicted by the embedding model are optimal. The transistor’s PAE when terminated with the embedding model’s predicted terminations reaches 71%, in close agreement to the transistor’s PAE when terminated with the embedding model’s predicted terminations at peak power.

Index Terms—Nonlinear modeling, GaN, HEMT, ASM-HEMT, Class F, X-Band

I. INTRODUCTION

A. Design of Radio Frequency Power Amplifiers

Gallium nitride high electron mobility transistors (GaN HEMTs) which offer current state-of-the-art performance for radio frequency (RF) power amplifiers (PAs), are deployed in both 4G and 5G communication infrastructure [1]. Much of the successful application of a transistor in a circuit, GaN HEMT or otherwise, depends on the transistor model and its ability to accurately simulate the nonlinear behavior of the transistor. GaN HEMTs, as a device of high interest, has had several different models developed by a wide range of research groups. These models range from empirical models such as the Angelov model [2], to compact physical models like the ASM-HEMT model [3], or the MIT Virtual Source GaNFET-high voltage model [4].

Transistor models are crucial in the field of RF circuit design. Once a modeler has extracted a nonlinear model that matches well the measured data from a selected transistor, high-performance PAs in every class of operation can be designed. However, this is typically done after much simulation of the transistors using multi-harmonic source-pull and load-pull. Indeed, the more power efficient modes of PA operation require special design considerations at the fundamental and harmonic frequencies in both the amplifier’s input and output matching networks.

Moreover, harmonic terminations are not independent of each other or the fundamental, so a truly exhaustive search of the transistor’s optimal terminations at a given mode of operation increases exponentially past the initial load or source-pull at the fundamental frequency [5]. This process is time-consuming when pursued via simulation. When pursued experimentally, it is labor-intensive and ties up valuable resources in a lab for a prolonged period of time.

B. Nonlinear Embedding Models

An alternative approach to PA design lies in a reconfiguration of the transistor model itself. Nonlinear embedding models are modified transistor models that allow for simulation software to directly interact with the current generators at the intrinsic reference planes of the transistor model.

Simulating at the current-source reference planes of the transistor gives a designer the ability to fully control the internal mode of operation of the device using simple ideal terminations or waveforms. The embedding model then projects the waveforms at the current-source reference planes to the extrinsic reference planes while accounting for the nonlinear charges and parasitics of the full transistor model. This concept is illustrated in Fig. 1(a) in contrast with the standard configuration in Fig. 1(b).

Power amplifier design with a nonlinear embedding model bypasses the time-consuming load and source-pull searches used in the conventional PA design process by directly prescribing the desired internal mode of operation and predicting the required optimal source and load terminations at the

![Fig. 1: (a) Embedding model with accessible intrinsic nodes. (b) Standard model modified with inspection nodes to determine model behavior at current source reference plane.](image-url)
A. Prediction of Class F Terminations using ASM-HEMT Nonlinear Embedding Model

A Class F simulation was first completed at the current-source planes, when the output of the transistor model is not affected by its parasitics, allowing for near-ideal operation of the transistor. Ideal shorts at the second and fourth harmonics, and ideal opens at the third and fifth harmonics were applied at the drain terminal. The gate and drain current and voltage waveforms at the current source reference planes are then projected through the extrinsic and manifold layers up to the manifold reference planes. The $\Gamma_L(n\omega)$ and $\Gamma_S(n\omega)$ at the manifold reference planes for the fundamental to the third harmonic are calculated from the gate and drain voltages and currents. Note that the embedding process does not affect the Class F operation of the transistor at the intrinsic plane. In some cases, the projected terminations are located outside of the Smith Chart, indicating that an active load is required to maintain Class F operation. In this scenario, the lossless intercept (i.e. $|\Gamma_{S,L}| = 1$) with the same phase will be retained for the experimental validation.

For the best results, it was necessary to test a variety of different resistance values for the load at the fundamental frequency and compare them with respect to the desired figure of merit. In the case of PAE, it was found in simulation that terminating the modeled transistor with lower $R_L$ values ($\leq 225\ \Omega$) resulted in a lower predicted PAE but a higher peak output power. Conversely, higher $R_L$ values ($\geq 300\ \Omega$) result in a higher peak PAE, but a lower peak output power. For this particular transistor a good compromise between PAE and output power was found by selecting $R_L$ to be 275 $\Omega$.

B. Simulation of Predicted Class F Operation using ASM-HEMT Model

Once the terminations at the measurement planes have been found and changed to their lossless intercept, they are applied to a separate Class F simulation using the standard ASM-HEMT model at the manifold planes. The input power is now applied at the gate side of the manifold reference planes of the transistor model and terminated with the lossless harmonic
terminations $\Gamma_{S,L}$ shown in Table I (right column). From this verification simulation, the predicted peak PAE for the transistor was 69%.

C. Experimental Validation of Nonlinear ASM-HEMT Model

To experimentally validate the optimal Class F terminations predicted by the embedding model, the source and load terminations were synthesized in the laboratory and applied to the physical transistor under consideration. The measurement was captured using a Keysight PNA-X in NVNA mode driven with Maury Microwave’s IVCAD software. The terminations were realized either with passive or hybrid-active loads using, respectively, a tuner or a combination of tuner and signal injection.

For the passive experiment, the fundamental load impedance from Table I predicted by the embedding model was used and applied to the transistor with the harmonics left uncontrolled. For the hybrid-active experiment, a passive tuner was used for the fundamental load impedance and a combination of tuner and signal injection to provide a termination closer to $|\Gamma_{S,L}| = 1$ for the second and third load harmonics and the second source harmonic. The terminations used for each mode are given in Table I (right column).

Figure 2 shows a comparison of the PAE between the passive and hybrid-active experiments across input power. The most notable feature of the comparison is the 12 point PAE increase from 58% to 71% at peak power between the two termination schemes. The PAE increase can be attributed to the introduction of the predicted second and third harmonic terminations for class F operation. This improvement comes at no expense to output power and transducer gain, as seen in Fig. 2(b). Figure 2 also shows a good agreement between the

Fig. 3: (a) Measured PAE across a phase sweep of the second harmonic’s load termination for three separate transistors. (b) Smith chart showing the load terminations used for each harmonic during the sweep.

Fig. 4: (a) Measured PAE across a phase sweep of the third harmonic’s load termination for three separate transistors. (b) Smith chart showing the load terminations used for each harmonic during the sweep.
This plot shows a significant variation of the PAE across in a range of 100° around the predicted phase. The plot also reveals the proximity of the predicted optimal phase to the measured peak, indicating the accuracy of the embedding model prediction for the third harmonic load termination. In Fig. 5(b), a similar trend is seen with regards to the phase of the source’s second harmonic termination. This figure further confirms the accuracy of the embedding model prediction for the second harmonic source termination.

III. CONCLUSION

This paper presented an experimental validation of an alternative approach to RF power amplifier design. Using a nonlinear embedding model for developed for the ASM-HEMT compact transistor model, an optimal set of source and load terminations were determined at the fundamental, second, and third harmonics for Class F operation for a GaN HEMT at 10 GHz. The harmonic terminations projected to the edge of the Smith chart were used in an hybrid-active experimental setup with the modeled transistor. A PAE of 71% was recorded at peak output power for the predicted terminations and verified to be optimal using phase sweeps for each of the source and load harmonic terminations considered.

ACKNOWLEDGMENT

We would like to acknowledge Dr. Marek Mierzwinski of Keysight Technologies for his knowledge of ADS and crucial contributions to this project.

This material is based upon work supported by the Air Force Office of Scientific Research, under award number FA9550-21-1-0290 (Test and Evaluation portfolio) and KBR, under award number APSC02189.

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